Tungsten Powder Test at HiRadMat
Experiment Details

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Contents

• Analysis of beam / powder target interaction

• Details of the vessel / sample holder

• Instrumentation

• Activation calculations

• Experimental procedure
Energy Deposition in a tungsten powder sample

- Sample is a mixture of tungsten and helium, 50% solid fraction by Volume
- Proton Beam Kinetic Energy = 440GeV/c
- Beam Sigma = 2mm in x and y directions
- Peak Energy Deposition occurs at z≈12cm
- We chose a 30 cm long test sample
- In HiRadMat we can tune the protons-per-pulse to vary the deposited energy density in the sample

Energy deposited in a tungsten powder sample from FLUKA simulation
Energy Deposition in a tungsten powder sample

- Most of the energy is deposited in the solid fraction but a small fraction of the total energy is deposited in the gas fraction.
- We assume that the energy deposited per unit mass is equivalent for each component of the compound.

\[
E_{mix} = E_1 + E_2
\]

\[
\frac{E_1}{M_{f1}} = \frac{E_2}{M_{f2}}
\]

\[
e_1 = \frac{E_1}{V_{Vf1}}, \quad e_2 = \frac{E_2}{V_{Vf2}}
\]

\[
\Delta T_1 = \frac{e_1}{\rho_1 C_1}, \quad \Delta T_2 = \frac{e_2}{\rho_2 C_2}
\]

Energy deposited in the solid and gas fractions (from FLUKA)
Powder Eruption Mechanism: Timescales

Eruption mechanism time-scales

- **0-10 microseconds**
  Tungsten powder and helium are heated by the beam interaction lasting a few microseconds. During this time the pressure of the helium within the sample increases as the heating occurs before the gas can escape.

- **0-25 milliseconds**
  Pressurised helium accelerates and escapes into lower pressure helium above powder sample. Helium velocity transient peaks over a few milliseconds and then reduces as the pressure equalises.

Eruption energy deposition threshold

- **Below energy deposition threshold**
  helium escapes through the powder as though it was passing through a porous medium without disturbing the powder

- **Above energy deposition threshold**
  helium velocity is sustained at high enough level for long enough to aerodynamically lift some of the powder
Temperature jump after spill of 1e12 protons on target containing tungsten particles and helium gas.

Model region at peak energy deposition.

Temperature after beam spill in the tungsten grains:
- 1049K
- 300K

Temperature after beam spill in the helium gas:
- 332K
- 300K

Powder Eruption Mechanism: CFD Modelling.
CFD Results – Powder Jump with helium gas

Time=0s

20 m/s

0 m/s

helium velocity

Time=25ms
# Design of the Vessel / Sample Holder

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Description</th>
<th>Hazard</th>
<th>Precautions</th>
<th>Likelihood</th>
<th>Severity</th>
<th>Risk Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Set-Up</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
| 1  | Pre-existing activation of the experimental area       | Remnant activation from previous uses of the HIRadMAT tunnel                                                                                                   | Radiation dose                              | • Off-line setup  
• Installation via a remotely controlled crane  
• Observe the CERN radiation access controls  | 1         | 4        | 4           |
| 2  | Powder handling                                      | The tungsten powder sample has a size distribution containing everything below 250 microns                                                                   | Inhalation of fine particulate material       | • Minimise the required powder sample volume  
• Handle powder in a well ventilated area  
• PPE - mask, gloves, overcoat  
• Transport powder in a sealed container  | 2         | 2        | 4           |
|    | **Running the Experiments**                          |                                                                                                                                                            |                                             |                                                                                                                                               |           | 2        | 4           |
| 3  | Loss of powder containment                            | Optical Window Rupture                                                                                                                                          | Radioactive powder dispersal into the environment. Potential for inhalation of fine radioactive particulate material | • Double containment  
• Robust engineering design, tolerances, etc  
• Minimise the required powder sample volume  
• Minimise the activation level (number of primary protons)  
• Pressure relief valve  
• Monitor pressure inside the primary containment  
• Monitor temperature at the vessel wall  
• Cross-check the FLUKA calcs with a 2nd independent code  | 2         | 4        | 8           |
|    | Beam Window Rupture                                   |                                                                                                                                                            |                                             |                                                                                                                                               |           | 2        | 4           |
|    | Sample vessel Rupture                                 |                                                                                                                                                            |                                             |                                                                                                                                               |           | 2        | 4           |
|    | Seal failure                                           |                                                                                                                                                            |                                             |                                                                                                                                               |           | 2        | 4           |
| 4  | Fire / explosion                                      | Ignition of metallic powder                                                                                                                                       | Damage to apparatus. Potential release of radioactive material | • Minimise the required powder sample volume  
• Inert gas (Helium) environment inside the sample vessel  
• Inert gas inside the secondary containment also  | 1         | 4        | 4           |
| 5  | Sample contamination                                  | e.g. water from the cooling circuit, air from the tunnel, etc                                                                                                 | Nasty radiochemical effects, corrosion etc  | • Double containment  
• Inert gas (Helium) environment inside the sample vessel  | 1         | 4        | 4           |
| 6  | Experiment Diagnostics                                | Perform measurements in a high radiation area                                                                                                                  | Prompt radiation dose, activation of equipment | • Remote diagnostics only  
• Observe the CERN radiation access controls  
• Activated instrumentation treated as radioactive waste  | 1         | 4        | 4           |
|    | **Decommissioning**                                   |                                                                                                                                                            |                                             |                                                                                                                                               |           | 2        | 4           |
| 7  | Loss of powder containment during handling operations | The powder sample must be transported to a storage area to allow for a cool-off period                                                                          | Radioactive powder dispersal into the environment. Potential for inhalation of fine radioactive particulate material | • Trial the handling operations  
• Maintain the double containment during transport operations  
• Design to minimise the volume of contaminated waste material  
• Design for remote extraction of the sample vessel from the outer box  
• Extraction to take place in a glove-box/extractor hood environment  
• Extract directly into a bag/flask, i.e. restore the double containment  | 2         | 4        | 8           |

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23 April 2011
## Design of the Vessel / Sample Holder

### Precautions for the Experiment: (ALARA principle)

- Offline setup
- Remote instrumentation/diagnostics
- Double containment of the powder
- Pressure-rated vessel
- Inert gas environment

### Table: Precautions per Activity

<table>
<thead>
<tr>
<th>#</th>
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<tr>
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<td>The tungsten powder sample has a size distribution containing everything below 250 microns</td>
<td>Inhalation of fine particulate material</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Loss of powder containment</td>
<td>Optical Window Rupture</td>
<td>Radioactive powder dispersal into the environment. Potential for inhalation of fine radioactive particulate material</td>
<td>• Offline setup</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beam Window Rupture</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sample vessel Rupture</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seal failure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
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<td>Sample contamination</td>
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<td>• Offline setup</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extraction of the sample vessel from the outer box</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*HiRadMat Scientific Board Meeting, 23 April 2011*
Double Containment Vessel

Outer containment vessel

Inner containment vessel

Beam

LDV/camera

Lift Table
Energy deposited in a cross-section through the sample
Grain Size Distribution in the Powder Sample

- Have characterised the grain size distribution in the powder sample, important to determine the lift/drag characteristics.
- Will keep an “uniradiated” sample for future analysis.

Analysis by laser interferometry

Analysis by Sieve shaker
<table>
<thead>
<tr>
<th>Part Name</th>
<th>DRS No.</th>
<th>Material</th>
<th>Mass (g)</th>
<th>Quantity</th>
<th>Total Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Box Sides</td>
<td>TD-1183-882</td>
<td>Al Alloy 6082</td>
<td>11000</td>
<td>1</td>
<td>11000</td>
</tr>
<tr>
<td>Inner Box Cover</td>
<td>TD-1183-902</td>
<td>Al Alloy 6082</td>
<td>8800</td>
<td>1</td>
<td>8800</td>
</tr>
<tr>
<td>Outer Box Base Plate</td>
<td>TD-1183-821</td>
<td>Al Alloy 6082</td>
<td>6600</td>
<td>1</td>
<td>6600</td>
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<tr>
<td>Glass Window</td>
<td></td>
<td>Glass</td>
<td>1809</td>
<td>2</td>
<td>3618</td>
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<tr>
<td>Light Bracket Post</td>
<td>TD-1183-941</td>
<td>Copper OFHC</td>
<td>578</td>
<td>6</td>
<td>3468</td>
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<tr>
<td>Inner Box Base Plate</td>
<td>TD-1183-901</td>
<td>Al Alloy 6082</td>
<td>2703</td>
<td>1</td>
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<tr>
<td>Optical Window Retainer</td>
<td></td>
<td>Al Alloy 6082</td>
<td>603</td>
<td>2</td>
<td>1206</td>
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<tr>
<td>St. Steel Valves/Pipes</td>
<td></td>
<td>St. Steel</td>
<td>1091</td>
<td>1</td>
<td>1091</td>
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<tr>
<td>Tungsten Powder</td>
<td></td>
<td>Tungsten</td>
<td>850</td>
<td>1</td>
<td>850</td>
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<tr>
<td>Outer Box Feedthrough Flange</td>
<td>TD-1183-931</td>
<td>St. Steel</td>
<td>774</td>
<td>1</td>
<td>774</td>
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<tr>
<td>Powder Trough Saddle</td>
<td>TD-1183-905</td>
<td>Titanium Alloy (TiAl4V)</td>
<td>300</td>
<td>2</td>
<td>600</td>
</tr>
<tr>
<td>M6x16 Screws</td>
<td></td>
<td>A2 St. Steel</td>
<td>5.5</td>
<td>96</td>
<td>528</td>
</tr>
<tr>
<td>M6x25 Screws</td>
<td></td>
<td>A2 St. Steel</td>
<td>7.2</td>
<td>44</td>
<td>316.8</td>
</tr>
<tr>
<td>Beam Window Flange</td>
<td>TD-1183-804</td>
<td>Al Alloy 6082</td>
<td>66</td>
<td>4</td>
<td>264</td>
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<tr>
<td>Pressure Sensor</td>
<td></td>
<td>St. Steel/Plastic</td>
<td>120</td>
<td>2</td>
<td>240</td>
</tr>
<tr>
<td>Brass Valves/Pipes</td>
<td></td>
<td>Brass</td>
<td>217</td>
<td>1</td>
<td>217</td>
</tr>
<tr>
<td>Tungsten Powder Holder - Inner</td>
<td>TD-1183-903</td>
<td>Pure Titanium</td>
<td>101</td>
<td>1</td>
<td>101</td>
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<tr>
<td>Tungsten Powder Holder - Outer</td>
<td>TD-1183-904</td>
<td>Pure Titanium</td>
<td>89</td>
<td>1</td>
<td>89</td>
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<tr>
<td>Beam Window</td>
<td>TD-1183-808</td>
<td>Titanium Alloy (TiAl4V)</td>
<td>22</td>
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<td>88</td>
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<tr>
<td>M4x16 Screws</td>
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<td>A2 St. Steel</td>
<td>2.1</td>
<td>32</td>
<td>67.2</td>
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<td>LED cluster</td>
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<td></td>
<td>4</td>
<td>12</td>
<td>48</td>
</tr>
<tr>
<td>Extra Screws</td>
<td></td>
<td>A2 St. Steel</td>
<td>44</td>
<td>1</td>
<td>44</td>
</tr>
<tr>
<td>Window Packer Gasket</td>
<td></td>
<td>Cellulose</td>
<td>15</td>
<td>2</td>
<td>30</td>
</tr>
</tbody>
</table>

**Mass (g) Content by Material**

- **Brass**: 30573 g
- **Copper OFHC**: 3618 g
- **Al Alloy 6082**: 3468 g
- **A2 St. Steel**: 30573 g
- **Ti Alloy (Ti6Al4V)**: 217 g
- **Pure Titanium**: 217 g
- **Tungsten**: 850 g
- **Glass**: 43 kg total mass
Temperature Jump in Vessel Components

• Predicted eruption threshold is well below the melting temperature of tungsten

Note: We do not intend to induce melting in the tungsten grains. We would never design a target to operate at a level where the grains melt, and as such, this is not seen as a useful regime.
Dynamic Stress in the Grade-5 Titanium Beam Window

- ANSYS simulations indicate that the peak dynamic stress in the beam window is significantly reduced if the beam pulse lasts for several acoustic wave periods (several x 0.3 µsec in the case of a 1mm thick titanium window).

Note: Reduction in stress achieved by extending the duration of the beam spill. We have a factor of ~4 on yield stress at the predicted eruption threshold.

Note: Large dynamic stresses when the beam spill is short.

2e12 ppp delivered in 0.45 micro-sec

2e12 ppp delivered in 1.8 micro-sec
CFD Model of Pressure rise in sealed sample holder

Inner containment vessel rated for 2 bar internal pressure

As a result of convection between gas and hot powder the gas temperature and pressure in the sample holder increase.

Peak pressure and temperature depend on cooled surface area of container.
Sample cool down time (time between shots)

\[ Q = h_1 A_1 (T_1 - T_2) = h_2 A_2 (T_2 - T_3) = UA (T_1 - T_3) \]
\[ \frac{dT_1}{dt} = \left( \frac{UA}{mCp} \right) (T_1 - T_3) \]

- Wall temperature (t3) maintained by water-cooled base
- Sample temperature (t1) depends on pulse intensity
- Exponential temperature decay – depends on natural convection between powder and helium and between helium and cooled containment box
- In 7 minutes the temperature has returned to within 1% of its value before the pulse
Instrumentation

• High Speed Remote video to record the powder eruption
  – Line of sight via two mirrors
  – 40m remote distance

• Laser Doppler Vibrometer to measure response of the trough wall

• PT100 Temperature sensors
  – Inner vessel wall
  – Lighting rig heat sinks

• Pressure sensors to monitor pressure fluctuations inside the vessel
  – Absolute pressure inside inner containment vessel
  – Absolute pressure inside outer containment vessel

To record the response of the target and its container
To monitor changes in the sample environment
High-Speed Video Equipment

• Camera
  – MotionXtraHG-100K camera
  – Remote trigger
  – Can record 800x600 pixels @3000 fps
  – Longest acquisition time 1.5 seconds

• Optics
  – To view an area 12x9cm from 40m away
  – Reflex-Nikkor 1000mm f/11 mirror lens
  – Nikon TC-200 teleconverter

• Trials
  – Have demonstrated applicability of this hardware

*Right: video clip showing tungsten powder falling from a funnel at ~1m/s. It is played at 1/100 speed. Note the 1cm divisions in the background.*
Lighting Rig

- LED lighting in close proximity to sample for maximum luminosity
  - 12x10-LED OSLON clusters
  - Mounted on copper heat sinks
  - Remote power supplies

- Typical LED degradation characteristic as a result of proton irradiation (Johnston et al.)

![Image of lighting rig](image1.jpg)

![Image of degradation graph](image2.jpg)
Activation Studies: FLUKA Model Geometry

- Irradiation Profile used in the simulations: \(1 \times 10^{13}\) protons in 1 second – 440GeV/c, \(\sigma = 2\)mm
- Cooling times: 1 hour, 1 day, 1 week, 1 month, 2 months, 4 months
- Precision simulations: EMF-ON, residual nuclei decays, etc…
Activation Dose Rates ($\mu$Sv/h)

- **1 hour**: Maximum dose rate on the sample: 3.7 $Sv/h$
- **1 day**: Maximum dose rate on the sample: 103 $mSv/h$
- **1 week**: Maximum dose rate on the sample: 9 $mSv/h$
- **1 month**: Maximum dose rate on the sample: 925 $\mu$Sv/h
- **2 months**: Maximum dose rate on the sample: 476 $\mu$Sv/h
- **4 months**: Maximum dose rate on the sample: 241 $\mu$Sv/h
## Container Activation – In Contact

<table>
<thead>
<tr>
<th>Cooling time</th>
<th>Outer Vessel Dose Rate [uSv/h] – Top of container</th>
<th>Inner Vessel Dose Rate [uSv/h] – Top of container</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hour</td>
<td>2.74 x 10^4</td>
<td>5.14 x 10^4</td>
</tr>
<tr>
<td>12 hours</td>
<td>3.00 x 10^3</td>
<td>5.79 x 10^3</td>
</tr>
<tr>
<td>1 day</td>
<td>1.55 x 10^3</td>
<td>2.90 x 10^3</td>
</tr>
<tr>
<td>1 week</td>
<td>49.0</td>
<td>113</td>
</tr>
<tr>
<td>1 month</td>
<td>5.0</td>
<td>12</td>
</tr>
<tr>
<td>2 months</td>
<td>3.0</td>
<td>6</td>
</tr>
<tr>
<td>4 months</td>
<td>1.79</td>
<td>3.98</td>
</tr>
</tbody>
</table>

- A cool-down time of 1 year is foreseen
- We do not plan to remove the powder sample from its container post irradiation
Area Activation – 1h

After 1 hour of cooling time, access is possible in TJ7
Experimental procedure

Experiment broken down into three areas:

1. **Trough wall response:**
   start at “low” intensity (well below eruption threshold). Repeat a number of identical beam pulses. Look for difference in response between inner and outer trough walls using the LDV.

2. **Ramp up the intensity towards the predicted eruption threshold:**
   look for a powder eruption with the high speed camera. Continue to monitor the trough wall with the LDV. A significant eruption signals the end of the experiment because the powder will not be guaranteed to fall back into the trough!

3. **Beam position scan:**
   If on reaching the predicted threshold nothing has happened then we plan to move the beam axis closer to the powder free surface to increase the likelihood of an eruption

Recall: Minimum time between pulses of the order ~10 mins to allow for sample cooldown. Will monitor temperature of vessel wall and pressure inside the primary containment.
Pulse List

- Possible beam configurations are currently under discussion
- Would like to vary the pulse intensity (protons per pulse), while keeping constant the pulse bunch structure, beam energy, and beam sigma
- The outline below requires four distinct beam configurations, where some beam configurations are repeated multiple times (1a, 1b, 1c, etc...)
- We foresee a total budget of \( \sim 1 \times 10^{13} \) protons

<table>
<thead>
<tr>
<th>Shot No.</th>
<th>Beam Energy</th>
<th>Beam Sigma</th>
<th>No. Bunches in Train</th>
<th>Bunch Spacing</th>
<th>Total Pulse Length</th>
<th>No. Protons/bunch</th>
<th>Total Protons/pulse</th>
<th>Beam Depth in Powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>1.39( \times )10^9</td>
<td>5( \times )10^10</td>
<td>6mm=3( \sigma )</td>
</tr>
<tr>
<td>1a</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
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<tr>
<td>1b</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
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<td>5( \times )10^10</td>
<td>6mm=3( \sigma )</td>
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<tr>
<td>1c</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
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<td>6mm=3( \sigma )</td>
</tr>
<tr>
<td>2</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>2.78( \times )10^9</td>
<td>1( \times )10^11</td>
<td>6mm=3( \sigma )</td>
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<tr>
<td>3</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
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<td>6mm=3( \sigma )</td>
</tr>
<tr>
<td>4</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
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<td>1( \times )10^12</td>
<td>6mm=3( \sigma )</td>
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<tr>
<td>5</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>5.56( \times )10^10</td>
<td>2( \times )10^12</td>
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<td>6</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>5.56( \times )10^10</td>
<td>2( \times )10^12</td>
<td>5mm=2.5( \sigma )</td>
</tr>
<tr>
<td>6a</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>5.56( \times )10^10</td>
<td>2( \times )10^12</td>
<td>4mm=2( \sigma )</td>
</tr>
<tr>
<td>6b</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>5.56( \times )10^10</td>
<td>2( \times )10^12</td>
<td>3mm=1.5( \sigma )</td>
</tr>
<tr>
<td>6c</td>
<td>440 GeV/c</td>
<td>( \sigma_x=\sigma_y=2\text{mm} )</td>
<td>36</td>
<td>50 nsec</td>
<td>1.8 ( \mu )sec</td>
<td>5.56( \times )10^10</td>
<td>2( \times )10^12</td>
<td>3mm=1.5( \sigma )</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0( \times )10^13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Status and Plans

• Vessel Manufacture: completed in FY 2011/12

• Assembly and testing at RAL: currently underway

• Ship to CERN: 1st week in May

• Setup the experiment at CERN: 14 – 18 May

• Perform the experiment: 21 – 25 May